A Simple Model of Grabby Aliens

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Abstract

According to a hard-steps model of advanced life timing, humans seem puzzlingly early. We offer an explanation: an early deadline is set by "grabby" civilizations (GC), who expand rapidly, never die alone, change the appearance of the volumes they control, and who are not born within other GC volumes. If we might soon become grabby, then today is near a sample origin date of such a GC. A selection effect explains why we don't see them even though they probably control over a third of the universe now. Each parameter in our three parameter model can be estimated to within roughly a factor of four, allowing principled predictions of GC origins, spacing, appearance, and durations till we see or meet them.

1 Introduction

To a first approximation, there are two types of aliens: quiet and loud. Loud aliens last long, expand outward, and make visible changes. Quiet aliens fail on at least one of these criteria. Quiet aliens are harder to see, and so could be quite common, or not, forcing quite uncertain estimates of their density via methods like the Drake equation (1,2). Loud aliens, in contrast, could be quite noticeable if they exist in any substantial number per Hubble volume.

To study loud aliens, this paper focuses on a very simple model, one with only three free parameters, each estimable to within roughly a factor of four. This allows for much more precise estimates than does the Drake equation. Yes, more complex models than ours are possible, but simple models have many advantages.

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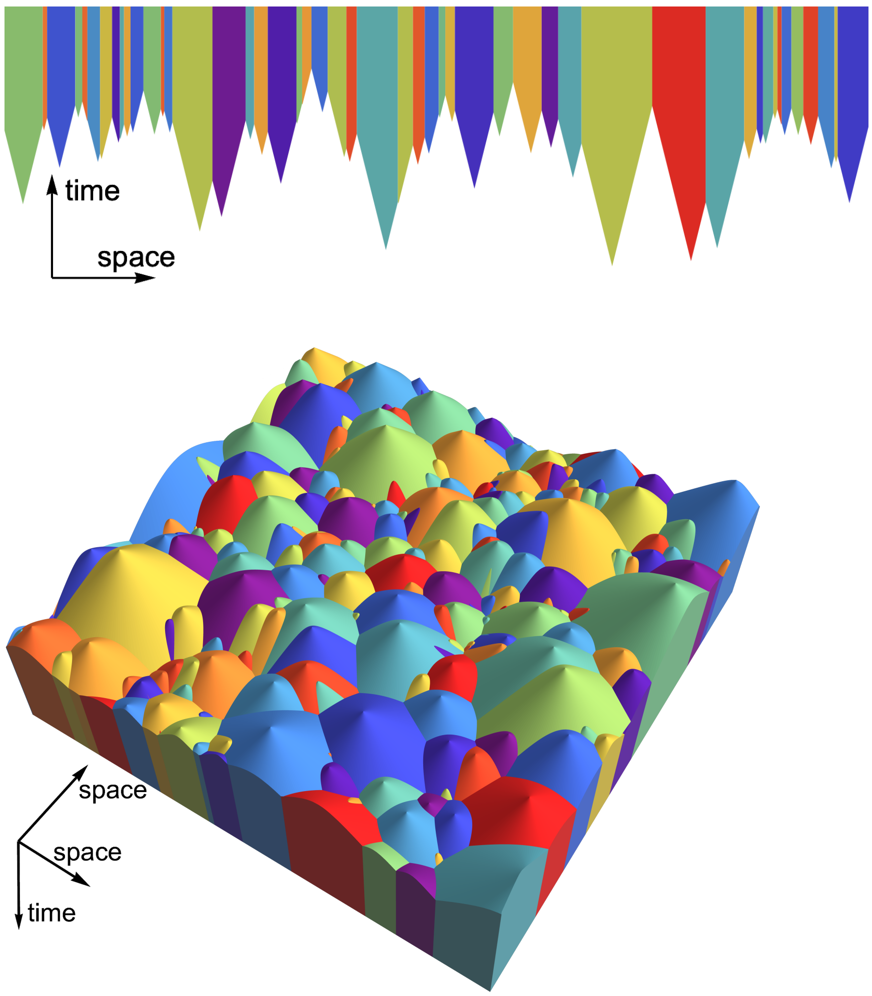

Figure 1. These two diagrams each show a sample stochastic outcome from a grabby aliens model, in one (1D) and two (2D) spatial dimensions. Figure 1A shows space on the x-axis and time moving up the y-axis. Figure 1B shows two spatial dimensions, with time moving downward into the box. A three-dimensional visualisation can be found at `https://grabbyaliens.com`.

In both cases, randomly-colored grabby civilizations (GCs) are each born at a spacetime event, expand in forward-time cones, and then stop upon meeting another GC. The scenarios shown are for a "power" n of 6. If the expansion is at 50% lightspeed, then the 1D diagram shows 49 GC across a spatial width of 18.8 Gly, while the 2D diagram shows 193 GC across a width of 41.7 Gly, both widths applying at median GC birthdate, if that is our current date of 13.8 Gyr. We show coordinates co-moving in space and conformal in time, as explained in Section 8.

Ours is a model of "grabby" aliens, who by definition a) never die alone, b) expand the volumes they control at the same speed, c) clearly change the look of their volumes (relative to uncontrolled volumes), and d) are not born within GC-controlled volumes. (See Figure 1 for examples of the space-time pattern produced by this model.)

Our first model parameter is the rate at which grabby civilizations are born. We assume that we humans have non-zero chance of giving birth to a grabby civilization, and that, if this were to happen, it would happen within roughly ten million years. We also assume that our chance is space-time-representative, in that we have no good reason to expect that our spacetime location is unusual, relative to other GCs. Given these assumptions, and the fact that we do not now seem to be within a "clearly changed" alien volume, our current spacetime event becomes near a sample from the distribution of grabby civilization origins. That allows us to estimate the grabby birth rate to within roughly a factor of two (for its inter-quartile range), at least for "powers" (explained below) over 3. (Our assumptions reject the "zoo" hypothesis (3).)

Yes, it is possible, and perhaps even desirable, that our descendants will not become grabby. Even so, our current date remains a data point. Surprised? Imagine that you are standing on a strange planet wondering how strong is its gravity. Your intuition tells you, from the way things seem to bounce and move around you, that you could probably jump about 1.3 meters here, compared to the usual 0.5 meters on Earth. Which suggests that you are on a planet with a gravity like Mars. And it suggests this *even if you do not actually jump*. A counterfactual number can be just as valid a data point as a real number.

Our second model parameter is the (assumed universal) speed at which grabby civilizations expand. Our model predicts that at typical grabby origin dates, a third to a half of the universe is within grabby-controlled volumes. So if the grabby expansion speed were low, then many such volumes should appear very noticeable in our sky. However, if their expansion speed were within $\sim$25% of lightspeed, a selection effect implies that we would be more likely to not see than to see any such volumes (see Section 11). If we could have seen them, then they would be here now instead of us. As we do not now see such volumes, we conclude that grabby aliens, if they exist, expand fast.

Our third model parameter is the effective number of "hard steps" in the "great filter" process by which simple dead matter evolves to become a grabby civilization (4). It is well-known that the chance of this entire process completing within a time duration goes as that duration raised to the power of the number of hard (i.e., take-very-long) steps (or their multi-step equivalents) in that evolutionary process. Using data on Earth history durations, a literature estimates an Earth-duration-based power to lie roughly in the range 3-9 (5, 6, 7, 8, 9, 10, 11, 12, 13).

Such hard-steps power-law models are usually applied to planets. However, given sufficient variety in oasis origin times and durations, or a sufficient likelihood of panspermia (14), we will argue in Section 3 that such a power law can also apply to the chances of advanced life arising within a larger volume like a galaxy. (At least over a modest time range, and while such chances remain low.) This volume-based power is our third key parameter.

For each combination of our three model parameters, we can fully describe the stochastic spacetime patterns of GC activity across the universe, allowing us to estimate, for example, where they are and when we would meet or see them. We will show in detail

how these distributions change with our model parameters.

Our grabby aliens model can explain a striking but neglected empirical puzzle: why do we humans appear so early in the universe? Yes, a "galactic habitable zone" literature often finds our date to be not greatly atypical of habitable durations undisturbed by nearby sterilizing explosions, for both short and long durations (15, 16, 17, 18, 19, 20, 21, 22, 23, 24).

However, we will show that these calculations neglect the hard-steps power-law. When that is included, and assuming powers above two and the habitability of stars less massive than our sun, then humanity looks early. We will show this via another simple model, this one of advanced life origin dates. This origin date model applies the hard-steps power law to planets, and allows stars to form at different dates and to last for different durations. This model produces a time distribution over when advanced life should appear (if it ever appears), and says that less than 10% of this distribution appears before today's date, unless we make rather strong assumptions both about the hard-steps power and about the habitability of stars that last longer than our sun. (See Figure 2.)

Our grabby aliens model resolves this puzzle by denying a key assumption of this origin date model: that the birth of some advanced life has no effect on the chances that others are born at later dates (25, 26). Our grabby alien model instead embodies a selection effect: if grabby aliens will soon grab all the universe volume, that sets a deadline by which others must be born, if they are not to be born within an alien volume. So we can explain why we are early via the twin assumptions that (a) we could see but do not see alien controlled volumes, and (b) some of our descendants may soon become grabby.

This paper will now review the robustness of the hard steps model, use a simple origin date model to show how the hard-steps process makes humanity's birth date look early, describe the basic logic of our new model and how to simulate it, show how to change coordinates to account for an expanding universe, and then describe our model's specific predictions for grabby alien civilization times, distances, angles, speeds, and more.

2 The Hard-Steps Model

In 1983, Brandon Carter introduced a simple statistical model of how our civilization might rise from simple dead matter, via intermediate steps of life, complex life, etc., a model that he and others have further developed (5,6,7,8,9,10,11,12,13). Carter posited a sequence of required steps i, each of which has a rate $1/a_i$ per unit time of being achieved, given achievement of the previous step. The average of the duration t_i to achieve step i is a_i.

Assume that this process starts at $t = 0$ when a planet first becomes habitable, and that we are interested in the unlikely scenario where all of these steps are completed by time $t = T$. (That is, assume $\sum_i t_i < T$ while $\sum_i a_i \gg T$.) Assume also for convenience that steps divide into two classes: easy steps with $a_i \ll T$, and hard steps with $a_i \gg T$.

Conditional on this whole process completing within duration T, each easy step still on average takes about a_i, but each hard step (and also the time $T - E - \sum_i t_i$ left at

the end) on average takes about $(T - E)/(n + 1)$, regardless of its difficulty a_i. (Where $E = \sum_i a_i$ for the easy steps.) And the chance of this unlikely completion is proportional to T^n, where n is the number of hard steps.

This basic model can be generalized in many ways. For example, in addition to these "try-try" steps with a constant per-time chance of success, we can add constant time delays (which in effect cut available time T) or add "try-once" steps, which succeed or fail immediately but allow no recovery from failure. These additions still preserve the T^n functional form.

We can also add steps where the chance of completing step i within time t_i goes as t^{n_i}, for a step specific n_i. If all steps have this t^{n_i} form (try-once steps are $n_i = 0$, while hard try-try steps are nearly $n_i = 1$), then the n in T^n becomes $n = \sum_i n_i$ over all such steps i. (And this holds exactly; it is not an approximation.)

For example, a "try-menu-combo" step might require the creation of a species with a particular body design, such as the right sort of eye, hand, leg, stomach, etc. If the size of the available menu for each part (e.g., eye) increased randomly but linearly with time, and if species were created by randomly picking from the currently available menu for each part, then the chance of completing this try-menu-combo step within time t_i goes as t^{n_i}, where n_i is the number of different body parts that all need to be of the right sort.

We can also allow different planets (or parts of planets) to have different constants multiplying their T^n, for example due to different volumes of biological activity, or due to different metabolisms per unit volume. Such models can allow for any sorts of "oases" wherein life might appear and evolve, not just planets. And such models can accommodate a wide range of degrees of isolation versus mixing between the different parts of these volumes.

In a slightly less simple model, if planet lifetimes are proportional to star lifetimes, and if only stars with lifetimes $L < \bar{L}$ are suitable for advanced life, then the probability density function $\alpha(t)$ of advanced life to appear at date t is given by

$$\alpha(t) = \int_0^t x^{n-1} \varrho(t - x) \Big[H(\bar{L}) - H(x) \Big] dx, \tag{1}$$

where $\varrho(t)$ is the star formation rate (SFR) and $H[L]$ is a cumulative distribution function (c.d.f.) over planet lifetimes. The c.d.f. of stellar lifetimes L goes as roughly $H[L] = L^{1/2}$ over an important range (up to a max star lifetime $\bar{L} \sim 2 \times 10^4$ Gyr), because stellar mass m has c.d.f. that goes as $m^{-1.5}$, while stellar lifetime goes as m^{-3} (down to $\sim 0.08 M_\odot$). Note that as Equation (1) has $x < t$, and as $H[\bar{L}] - H[x]$ is nearly constant for $x \gg \bar{L}$, then t is nearly a power law when $t \ll \bar{L}$ and $\varrho(t)$ is a power law.

Furthermore, for the purposes of this paper we actually only need the SFR to be sufficiently well approximated by a power law over the actual range of times in which grabby civilizations are born. For example, we will see in Section 12 that for powers 3 or higher, over 90% of GCs are born within the date range 0.75 to 1.15, if the median GC birth date is set to 1. If the power law approximation fails at times outside this limited range, that just moves this range forward or back in time a bit, but preserves the validity of the model's stochastic pattern of spacetime events within this range.

We thus see that instead of being a peculiar feature of a particular model of the origin of advanced life, a t^n power law time dependence may be a robust feature of the great filter not just for individual planets, but also for (limited early-enough periods of) much larger co-moving volumes that contain changing mixes of planets and other possible oases.

In our grabby aliens model, we will thus assume that the chance for an advanced civilization to arise in each "small" (perhaps galaxy size) volume by date t after the big bang goes as t^n. We assume that this t^n form applies not just to the class of all advanced life and civilizations, but also in particular to the subclass of "grabby" civilizations.

3 How Many Hard Steps?

A literature tries to estimate the number of (equivalent) hard steps passed so far in Earth's history from key durations. Here is an illustrative calculation.

The two most diagnostic Earth durations seem to be the one from when Earth was first habitable to when life first appeared ($\sim$0.4Gyr), and the one remaining after now before Earth becomes uninhabitable for complex life ($\sim$1.2Gyr). Assuming that only e hard steps have happened on Earth so far (with no delays or easy steps), the expected value for each of these durations should be $\sim$5.4Gyr/$(e+1)$. Solving for e using the observed durations of 0.4 and 1.2 Gyr then gives e values of 3.5 and 12.5, suggesting a middle estimate of near 6.

The relevant power n that applies to our grabby aliens model differs from this e. It becomes smaller if evolution on Earth saw big delay steps, such as from many easy steps, in effect reducing Earth's $\sim$5.4 Gyr time window to complete hard steps. But the relevant power becomes larger than this e if there were hard steps before Earth (due to panspermia), or if there will be future hard steps between us today and a future grabby stage. The enormous complexity and sophistication of even the simplest and earliest biology that we know also seems to suggest higher powers n, most likely via panspermia (27, 28).

In the following, we will take power $n = 6$ as our conservative middle estimate, and consider n in 3 to 12 to be our plausible range, but at times also consider n as low as 1 and as high as 50.

4 How We Seem Early

Equation (1) above is a simple formula which can estimate the fraction of civilizations that arrive before some date, if they ever arrive. While for early times the chance $\alpha(t)$ will go as a power law if the SFR function $\varrho(t)$ is also a power law, a better SFR approximation can draw from the large empirical SFR literature. While this literature embraces a wide range of functional forms, the most common seems to be $\varrho(t) = t^{\lambda}e^{-t/\varphi}$, a form that peaks at $\chi = \lambda\varphi$.

The most canonical parameter estimates in this literature seem to be power $\lambda = 1$ and decay time $\varphi = 4$Gyr (29, 30, 31). However, as the SFR literature also finds a wide range of other decay times, we will consider three decay times: φ in $2, 4, 8$ Gyr, all of which we consider plausible.

We can also use this same functional form $\varrho(t) = t^{\lambda} e^{-t/\varphi}$ to approximate the many estimates produced in the "galactic habitable zone" (GHZ) literature. Such estimates are of the density at different times and places in our galaxy (and sometimes in other galaxies) of planets conducive to life or civilization. Such authors consider habitability not only due to suitable planets and stars, but also due to sufficiently low rates of nearby sterilizing explosions such as supernovae and gamma ray bursts (15, 16, 17, 18, 19, 20, 21, 22, 23, 24).

While the GHZ literature has attended mostly to dates before today, it almost always finds peak dates χ much later than the canonical SFR peak of $\chi = 4$Gyr, and often well after our current date of 13.8Gyr. We thus choose a habitable peak of $\chi = 12$Gyr as roughly matching typical GHZ literature estimates, and combine this with three decay times: ϱ in $2, 4, 8$ Gyr. The early rise to that peak often seems convex, fitting $\lambda > 1$.

(Our approach here of representing the GHZ via varying λ in effect marks most early stars as entirely unsuitable for life due to overly frequent nearby explosions. A more precise calculation would consider the specific duration lengths near each star between such explosions.)

Opinions in the literature vary regarding the relative habitability of lower mass stars. While the same planet should have the same metabolism at any star if its orbital radius gives it a habitable temperature, smaller stars may or may not have smaller planets, or fewer planets within a habitable orbit range. Increased solar flares and tidal-locking may also be larger problems for planets around smaller stars.

We use two model parameters to represent this variation in low mass star habitability. First, we allow variation in max planet lifetime $\bar{L}$, which we let vary from half of our sun's lifetime of $L_{\odot} \approx 10$Gyr (which is roughly Earth's lifetime) to the apparent max stellar lifetime of $\sim 2 \times 10^4$ Gyr. Second, we multiply the usual star mass c.d.f. $m^{-1.5}$ by a factor m^{κ}, to say that larger stars are this much higher of a habitability factor. This changes the planet lifetime c.d.f. to go as roughly $H[L] = L^{(3-2\kappa)/6}$. (When this is unbounded, we apply a low lifetime lower bound, which turns out not to matter.) We consider 0 and 3 as values for the *mass-favoring power* (MFP) κ.

In Figure 2, we show the percentile rank of today's 13.8 Gyr date within the predicted distribution of advanced life arrival dates, according to Equation 1. And we show how this rank varies with four parameters: GHZ decay $\varphi = 4$, mass-favoring power κ, hard-steps power n, and max planet lifetime $\bar{L}$ (Wolfram Research, Inc. '20). The appendix shows how results change as swe vary GHZ peak χ in $4, 8, 12$ Gyr.

Figure 2 suggests that GHZ decay φ and MFP κ make only modest differences relative to the effect of the power law, which is often overwhelming. For $\kappa = 0$ our percentile rank is below 1% for max lifetimes $\bar{L}$ beyond a trillion years, no matter what the values of other parameters. This also holds for $\kappa = 3$, when $n > 1.5$.

Given our favored power of $n = 6$, then even with a very restrictive lifetime $\bar{L} = 10$Gyr,

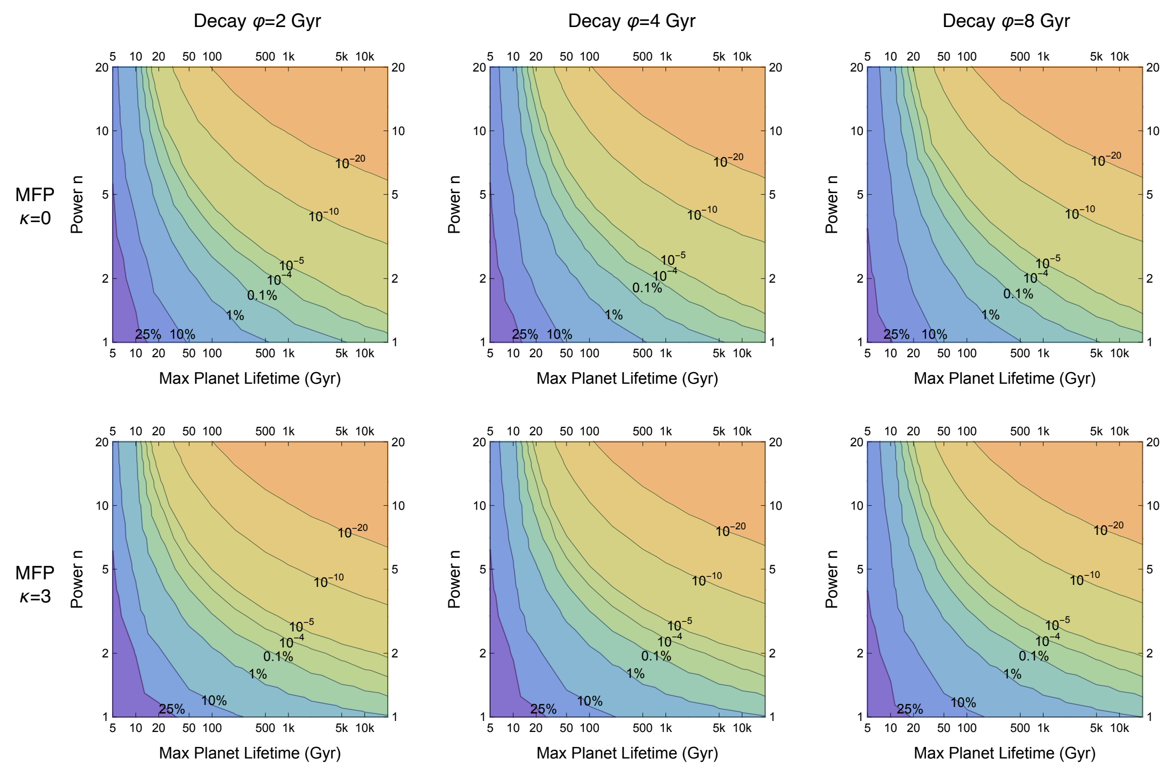

Figure 2. Percentile rank of today's 13.8Gyr date within the distribution of advanced life arrival dates, as given by equation (1). Six diagrams show different combinations of MFP κ and GHZ decay φ, while each diagram varies power n and max habitable planet lifetime $\bar{L}$.

all ranks are $< 10.6\%$. For power $n = 3$, at the low end of our plausible range, all ranks are 10% for lifetime $\bar{L} = 15$Gyr. And at power $n = 2$, all ranks are $< 8.4\%$ for lifetime $\bar{L} = 20$ when $\kappa = 0$, and $< 12.4\%$ when $\kappa = 3$.

Thus we are roughly at least 10% "surprisingly early" for $(n, \bar{L})$ combinations of $\{(6, 10), (3, 15), (2, 20)\}$. And modest increases in power n or max lifetime $\bar{L}$ beyond these values quickly make our rank look *very* surprisingly early. So unless one is willing to assume rather low powers n, and *also* quite restrictive max planet lifetimes $\bar{L}$, there seems to be a real puzzle in need of explanation: why have we humans appeared so early? (As the appendix shows, assuming earlier GHZ peaks χ allows somewhat higher n or more relaxed $\bar{L}$, but not by a lot.) Our grabby aliens model offers such an explanation.

5 Model Rationale

While our grabby alien model should ultimately stand or fall on how well it directly accounts for observations, readers may want to hear plausibility arguments regarding its key assumptions.

We have already discussed (in Section 2) reasons to expect a power law time dependence in the chances to originate advanced life early in any one place, due to evolution needing to pass through many difficult steps. We've also discussed how this kind of dependence can apply to large volumes like galaxies, as well to smaller ones like planets. But why might there exist civilizations who expand steadily and indefinitely, changing how their volumes look in the process?

In Earth history, competing species, cultures, and organizations have shown consistent tendencies, when possible, to expand into new territories and niches previously unoccupied by such units. When such new territories contain resources that can aid reproduction, then behaviors that encourage and enable such colonization have often been selected for over repeated episodes of expansion (32). (Note that individual motives are mostly irrelevant when considering such selection effects.)

In addition, expansions that harness resources tend to cause substantial changes to local processes, which induce changed appearances, at least to those who can sufficiently observe key resources and processes. While these two tendencies are hardly iron laws of nature, they seem common enough to suggest that we consider stochastic models that embody them.

Furthermore, when uncoordinated local stochastic processes are aggregated to large enough scales, they often result in relatively steady and consistent trends, trends whose average rates are set by more fundamental constraints. Examples include the spread of species and peoples into territories, diseases into populations, and innovations into communities of practice. Without wide coordination, local processes that induce local "death" seem unlikely to induce death correlated across very wide scales.

Yes, expanding into the universe seems to us today a very difficult technical and social challenge, far beyond current abilities. Even so, many foresee a non-trivial chance that some of our distant descendants may be up to the challenge. Furthermore, the large distances and times involved suggest that large scale coordination will be difficult, making it more plausible that uncoordinated local processes may aggregate into consistent overall trends. Also, the spatial uniformity of the universe on large scales, and competitive pressures to expand faster, suggest that such trends could result in a steady and universal expansion speed.

Yes, perhaps there is only a tiny chance that any one civilization will fall into such a scenario wherein internal selection successfully promotes sustained rapid overall expansion. Even so, the few exceptions could have a vastly disproportionate impact on the universe. If such expansions are at all possible, we should consider their consequences.

6 The Model

Our basic model sits in a cosmology that is static relative to its coordinates. That is, galaxies sit at constant spatial position vectors v in a D-dimensional space, time moves forward after $t = 0$, and constant speed movement in the x coordinate direction satisfies $s = \Delta x / \Delta t$ for speed s. (We are mainly interested in $D = 3$, but will sometimes consider

D in $1, 2$.)

Within this space, "grabby civilizations" (GC) spontaneously arise at events (v, t). By definition, GC volumes look clearly different, and expand in every direction at a constant local speed s until meeting volumes controlled by other GC. Once a volume is controlled by any GC, it is forever controlled by some GC.

Note that we allow the possibility of non-grabby civilizations (NGC), perhaps even a great many of them, whom GCs may or may not leave in peace. But our assumptions do require that NGCs only rarely block GCs from the activities that define them: expanding and changing volume appearances. And the larger a ratio we postulate between NGCs and GCs, the smaller a transition rate we must postulate for NGC to give birth to GC. For example, if in the history of the universe there have so far been a million times more NGC than GC, then, on the timescales seen so far, on average no more than one in a million NGC can give birth to a GC descendant.

Each "small" (perhaps larger than galaxy-sized) volume has the same uniform per-volume chance of a GC being born there, a chance that is independent of the chances in other volumes. Over time the chance of birth by t at some position v rises as $(t/k)^n$, a power n of time since $t = 0$ divided by a timescale constant. Except that this chance goes to zero as soon as the expanding volume of another GC includes this position v. As we discussed above, this power law dependence may be a robust feature of many models of the origin of life and civilization.

And that is our whole model. It has three free parameters: the speed s of expansion and the constant k and power n of the birthing power law. It turns out that we can estimate each of these parameters reasonably well.

Specific examples of the spacetime distribution resulting from this process are shown in Figure 1. Notice how smaller GC tend to be found at later origin times in the "crevices" between larger earlier GC. (For simplicity, these examples show each GC retaining control of its initial volume after meetings. Our analysis only depends on this assumption when we calculate distributions over final GC volumes.)

7 Heuristic 1D Model

A simple deterministic model gives a rough approximation to this stochastic model in one dimension.

Assume a regular array of "constraining" GC origins that all have the same origin time $t = x$, and which are equally spaced so that neighboring expansion cones all intersect at $t = 1$. (See Figure 3.) If these cones set the deadline for the origins of other "arriving" GC, we can then find a distribution over arriving GC origin times that results from integrating t^{n-1} over the regions allowed by the constraining GC.

The key modeling assumption of this simplified heuristic model is to equate the constraining GC origin time x with the *percentile rank* r of the resulting distribution of

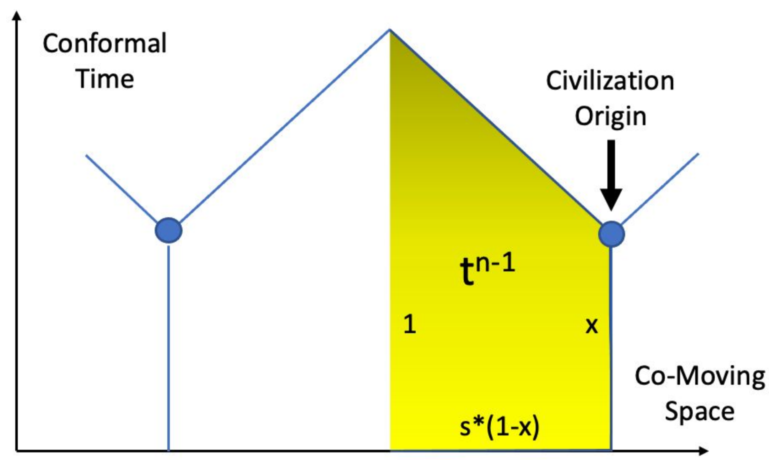

Figure 3. Illustration of the heuristic math model of Section 7

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arriving GC origins. This assumption implies

$$\frac{1-r}{r}\int_0^x t^{n-1}dt = \int_x^1 t^{n-1}\frac{1-t}{1-x}dt \tag{2}$$

and is independent of speed s or constant k. This math model captures two key symmetries of our stochastic model, which are described in Section 9.

For each power n, there is some rank r where this heuristic model's prediction $(1-x)/x$ equals a 1D simulation result for the ratio of median time till meet aliens to the median origin time. This rank is $\sim$0.88 at $n = 1$, falls to a minimum of $\sim$0.61 at $n = 4$, and then rises up to $\sim$0.88 again at $n = 24$. This simple heuristic math model thus roughly captures some key features of our full stochastic model.

8 Cosmology

Our model seems to have a big problem: its cosmology has things staying put, yet our universe is expanding. Our rather-standard solution: a change of coordinates.

Usually, using ordinary local "ruler" spatial distances dv and "clock" times dt, the metric distance d between events is given by $d^2 = dt^2 - dv^2$. We instead use "model" coordinates, which are co-moving spatial positions $du = dv/a(t)$ and conformal times $d\tau = dt/a(t)$. Here $a(t)$ is a "scale factor" saying how much the universe has expanded at time t relative to time $t = 1$. Metric distance then becomes $d^2 = a^2(t) \cdot (d\tau^2 - du^2)$.

In terms of our model spatial coordinates u, galaxies tend to stay near the same spatial positions. However, in an expanding universe a freely-falling object that starts at an initial speed $\Delta u/\Delta\tau$, and has no forces acting on it, does not maintain that $\Delta u/\Delta\tau$ coordinate speed as the universe expands. It instead slows down (33). Does this show

that a GC which might in a static universe expand at a constant clock speed $\Delta u/\Delta\tau$, not expand at constant model speed $\Delta u/\Delta\tau$ in an expanding universe?

No, because the frontier of an expanding civilization is less like an object thrown and more like the speed of a plane; a given engine intensity will set a plane speed relative to the air, not relative to the ground or its initial launch. Similarly, a civilization expands by stopping at local resources, developing those resources for a time, and then using them to travel another spatial distance (34). As this process is relative to local co-moving materials, it does maintain a constant model speed $\Delta u/\Delta\tau$.

We thus run our simulations in a static model space u, and in model time τ. To convert results from model time τ to clock time t, it suffices to know the scale factor function $a(t)$. This scale factor $a(t)$ went as $t^{1/2}$ during the "radiation-dominated" era from the first second until about 50,000 years after the big bang, after which it went as $t^{2/3}$ during the "matter-dominated" era. In the last few billion years, it has been slowly approaching $e^{\Omega t}$ as dark energy comes to dominate.

Assume that the scale factor is a power law $a(t) = t^m$, and that we today are at percentile rank r in the distribution over GC origin dates. If so, we can convert from model time τ to clock time t via $t = t_0 * (\tau/\tau_0)^{1/(1-m)}$ and $r = F(\tau_0)$, where $t_0 = 13.787$ Gyr is a best estimate of the current age of the universe, and $F(\tau)$ is the c.d.f. over GC model origin times. We can also convert between clock time power n and model time power n via $n' = n/(1-m)$.

Now, a least-squared-error fit of a power law to the actual $a(t)$ within 0-20 Gyr after the Big Bang gives a best fit of $m \approx 0.90$. However, as this m value tends to give more extreme results, we conservatively use $m = 2/3$ in most of our analysis. In the appendix, we show how some results change using $m = 0.9$.

Note that by assuming a uniform distribution over our rank r (i.e., that we could be any percentile rank in the GC origin time distribution), we can convert distributions over model times τ (e.g., an $F(\tau)$ over GC model origin times) into distributions over clock times t. This in effect uses our current date of 13.8Gyr to estimate a distribution over the model timescale constant k. If we use instead of $F(\tau)$, the distribution $F_0(\tau)$, which considers only those GCs who do not see any aliens at their origin date, we can also apply the information that we humans do not now see aliens.

In the rest of this paper we will show spacetime diagrams in terms of model coordinates (r, τ), but when possible we will talk and show statistics and distributions in terms of clock times, including clock time powers n.

9 Simulating The Model

Our stochastic model scales in two ways. That is, two kinds of transformations preserve its stochastic pattern of GC space-time origins. First, halving the speed s of expansion halves the average spatial distance between GC, but otherwise preserves their pattern. Second, changing timescale k changes the median GC origin time, but preserves the pattern once

times and distances are rescaled by the same factor to give the same median origin time as before.

So simulations need only vary dimension D and power n, and repeatedly sample, to see the full range of stochastic GC origin patterns that can be produced by this model. This simplifies our task of simulating this model. We can fix expansion speed at $s = 1$, focus on a unit time range $[0, 1]$ and unit volume $[0, 1]^D$, and use a "wrap around" (toroidal) metric which identifies $x = 0$ with $x = 1$, etc. in all spatial dimensions. (The appendix checks for robustness to these assumptions.) We generate N candidate GC origins (u, τ) as (uniformly) random positions v within this unit volume, paired with random times τ drawn from a c.d.f that goes as τ^n on $[0, 1]$.

Let us say that, for $s = 1$, spacetime event A "precludes" event B if A's time is earlier and if the spatial distance between them is less than their time difference. Given a set of N candidate origin events, we filter out any members precluded by other members, and the remaining set C of origins then defines a stochastic sample from our model. (It helps to test earlier candidates first, each against the test-passing origins collected so far.)

Except that we rescale all times and distances in C by the same factor to make the median origin time be one. We can then transform such a sample into a sample with a differing speed s by rescaling all distances. And we can transform it into samples with differing timescales k by rescaling the median origin time. (Such "samples" may describe the same basic stochastic pattern over larger or smaller spatial volumes, in essence holding more or less "copies" of the basic stochastic pattern.)

We know that a spacetime event is controlled by some GC if it is precluded by any GC origin. While a larger sample N of candidate GC origins tends to induce a larger non-precluded set C, eventually C stops increasing, giving a "full" sample. Lightspeed c can be varied relative to s to calculate who can see what in such a sample.

10 Simulation Statistics

Imagine one has a sample of simulation runs, each of which produces a set of C grabby civilization at origins (u, τ) within the model box $[0, 1]^3$. Here are some interesting statistics that one can calculate within each run (and average over multiple runs).

The following statistics depend only on the power n:

A) For each GC origin we can pick a (uniformly) random position u in the $[0, 1]^D$ volume, combine that with this GC origin time τ, and see if that event (u, τ) is precluded by any GC. Repeating this estimates the *volume fraction* of the universe which is controlled by GCs at that GC origin time τ. Repeating for all GCs can show how this volume fraction varies with GC origin rank.

B) We can collect a simulated distribution $F(\tau)$ over model GC *origin times* τ.

C) For each GC origin position, we can find the time τ at which a speed $s = 1$ traveler would arrive at that position from each other GC origin event. The minimum of

these is the *arrival time* when the first other GC expansion wave would, if allowed, arrive at this GC position.

D) The average of that min arrival time and this GC origin time is the *meet time*, when the two GC expansion waves will collide. The first GC it meets is also the first one to arrive.

The following statistics depend on both power n and speed ratio s/c:

E) Take the subset of GC who don't see any other GC-controlled-volume at their origin. For each such GC, if we assume Earth today has its rank r, that gives a constant for converting all model times into clock times. If we then assume a uniform distribution over Earth rank r (expressing the assumption that we have a representative chance of birthing grabby descendants), we can convert any distribution over model times into a distribution over clock times. We can also take any distribution over pairs of model times into a distribution over clock durations between those times. For each GC origin, we so far have three model times: origin, meet, and arrival. We can convert the model origin times into clock origin dates. And we can obtain clock durations between origin times and when they will meet aliens, or when aliens would arrive there.

F) Model box $[0,1]^3$ corresponds to ordinary physical volume $(13.8s/c\tau)^3\text{Gly}^3$ if today's date of 13.8Gyr corresponds to the median model time τ. Also, there are today $\sim$0.07 galaxies (each with mass $> 10^6 M_\odot$) per Mpc^3, which is 2×10^6 per Gly^3 (Conselice et al. 2019). Thus if galaxies are conserved, then for *any* time rank of humans in the model, the model box holds $G = 2 \times 10^6 (13.8s/c\tau)^3$ galaxies. So if sim run finds C civilizations, it has G/C *galaxies per GC* at sim end. At percentile r GC origin date, this is $(G/rC) *$ (volume fraction at r). (There are $\sim$7 times as many galaxies with mass $> 10^5 M_\odot$.)

G) If at some date, the model volume wherein a single GC is first to arrive is $V < 1$, then it covers $V * G$ galaxies at that date, at least if we assume that GCs who meet simply stop and retain control of their existing volumes. Iterating through the GC, a distribution over galaxies per GC can be found for different times.

H) A visible GC-controlled-volume would (unless it had already collided with another GC) appear as a disk in the sky with angle θ given by $\tan(\theta/2) = x/(c(b-x))$ where x solves $d^2 = x^2 + (c(b-x))^2$. We can thus find a distribution over the *max angle* that each GC can see. (If it sees none, its max angle is zero.)

I) Consider two GC origins. The later origin τ can see the earlier origin if their spatial distance d is less than cb, where b is their time difference. We can find a distribution over GCs of the number of other GC origins that each one can see at its origin. (This ignores the possibility that opaque GC volumes might block the view of others.)

Figure 4. Illustration of selection effect. When expansion speeds s are near lightspeed c, alien origin events in most of our backward lightcone would have created a GC that controls the event from which we are viewing, preventing here-now from becoming a candidate GC origin.

J) If a GC has not yet seen any other GC, it will first see the GC that it will first meet, and see it before their meeting. That *when see time* is $\tau = (d + \tau_0 + c\tau_1)/(1 + c)$, where τ_0 is the viewer's origin time, and τ_1 is the viewed's origin time.

K) We can convert origin and view times from model times into clock times, take the difference and get a distribution over clock *time until see* aliens. (That duration is zero if aliens can already be seen at GC origin.)

Code to simulate the grabby alien model and to compute the above statistics can be found at `https://github.com/jonathanpaulson/grabby_aliens`.

11 Estimating Expansion Speed

Our grabby aliens model has three free parameters, and we have so far discussed empirical estimates of two of them: the power n (in Section 3) and the power law constant k (in Section 8). The remaining parameter, expansion speed s, can also be estimated empirically, via the datum that we humans today do not see alien volumes in our sky.

We will see in Figure 10 that visible alien volumes are typically huge in the sky, much larger than the full moon. So there is only a miniscule chance of a visible volume being too small to be seen by the naked eye, much less by our powerful telescopes. So if alien volumes looked at all different, as we assume in our GC definition, and if their volumes intersected with our backwards light cone, we would clearly see them.

We will also see in Figure 7 that, averaging over GC origin dates, over a third of the volume of the universe is controlled by GCs. So from a random location at such dates, one is likely to see large alien-controlled volumes. However, if the GC expansion speed is a high enough fraction of the speed of light, a selection effect, illustrated in Figure 4, makes it unlikely for a random GC to see such an alien volume at its origin date.

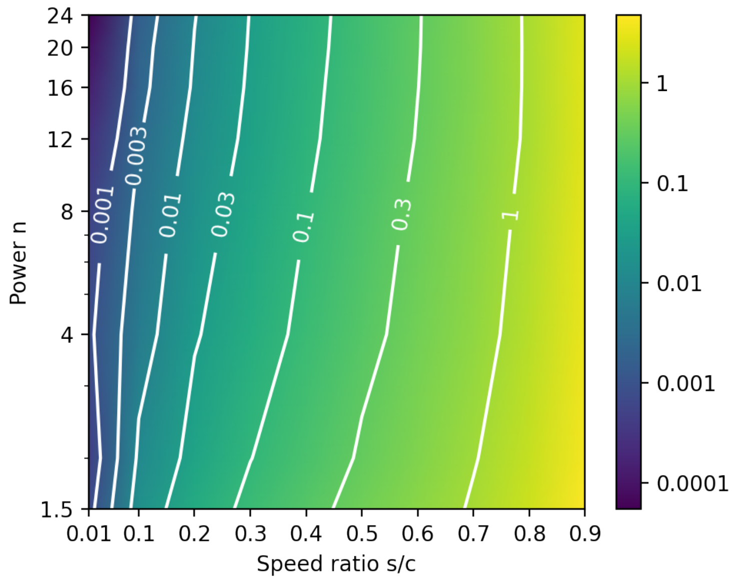

Figure 5. Likelihood ratios, for $(n, s/c)$ parameter pairs, regarding the observation that we see no large alien-controlled volumes in our sky. To compute a posterior distribution over these pairs, multiply this ratio by a prior for each pair, then renormalize.

Figure 5 shows how our evidence that we do not now see alien volumes updates our beliefs about the chances of various power and speed-ratio pairs $(n, s/c)$. It shows the ratio of the number of GC origin events that see no alien volumes in their sky, divided by the number that do see alien volumes. Speed ratios of $s/c < \sim 1/3$ are greatly disfavored, especially for high powers.

12 Simulation Results

This section contains many graphs showing how distributions over key statistics vary with power n, and sometimes also with speed ratio s/c. Unless stated otherwise, all numbers and curves shown average over 5 simulation repetitions, each with $L = 1, s = 1, c = 1$, and 10^8 sample GC origin events. Correctness of code has been checked by comparing independent implementations.

Figure 6 shows clock GC origin dates, and regarding those origin events Figure 7 shows volume-controlled fractions, Figure 8 shows clock durations til a descendant meets aliens, Figure 9 shows how many alien volumes are seen, Figure 10 shows the largest alien volume angle seen, and Figure 11 shows clock durations until a descendant sees aliens. Figure 12 shows how the number of galaxies per GC at the simulation end (when GCs fill all volumes) varies with power n, and Figure 13 shows many statistics collected together in a single diagram.

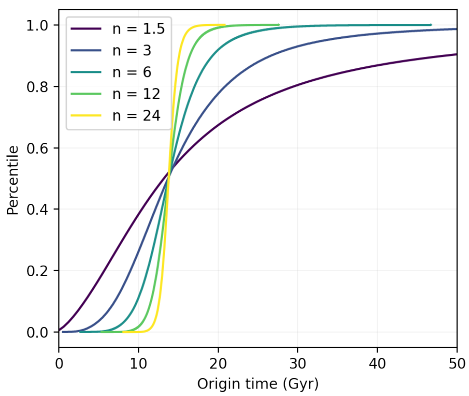

Figure 6. C.d.f.s over GC origin clock-times, assuming a uniform distribution over humanity's rank in this distribution. As this is for speed ratio s/c = 1, it ignores info that we see no aliens.

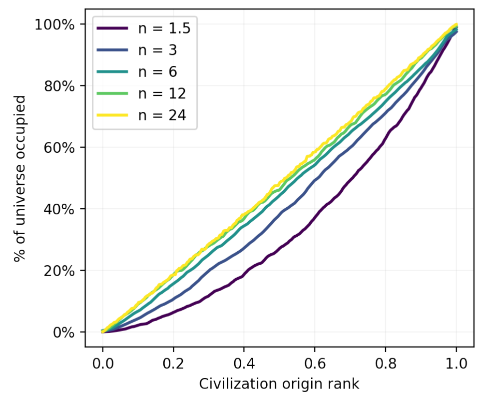

Figure 7. Fraction of universe volume controlled by GCs, as a function of rank of GC origin time.

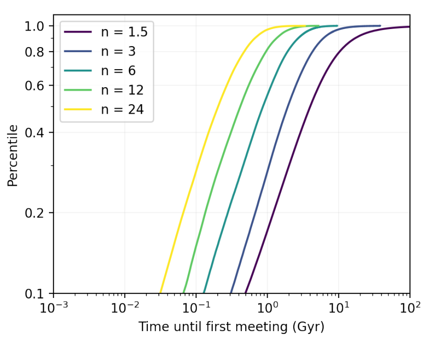

Figure 8. C.d.f.s over clock-time until some of our descendants directly meet aliens, assuming we give birth soon to a GC who has a uniform distribution over rank among GC origin times.

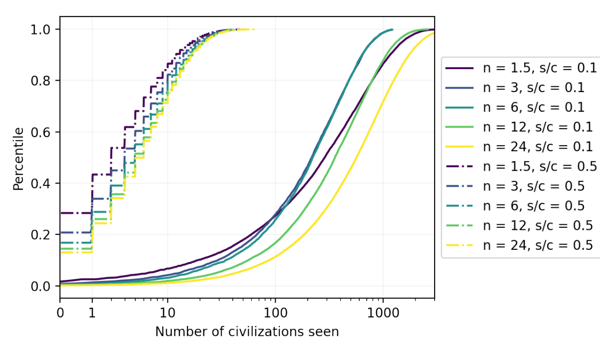

Figure 9. C.d.f.s over how many other GCs each one sees at its origin. At speed ratio $s/c = 1$, no GCs see any others at their origin.

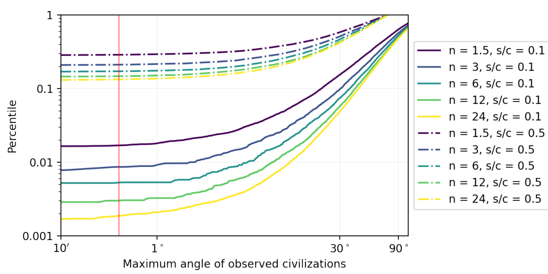

Figure 10. C.d.f.s over largest angle in sky of GC seen from GC origins. Red line is our Moon's diameter (29′20″).

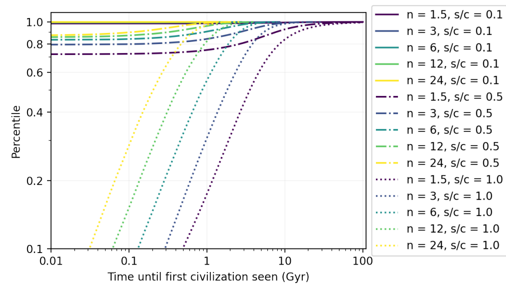

Figure 11. C.d.f.s over clock time till some GC descendant sees aliens. For s/c = 0.1, almost all GC have already seen aliens.

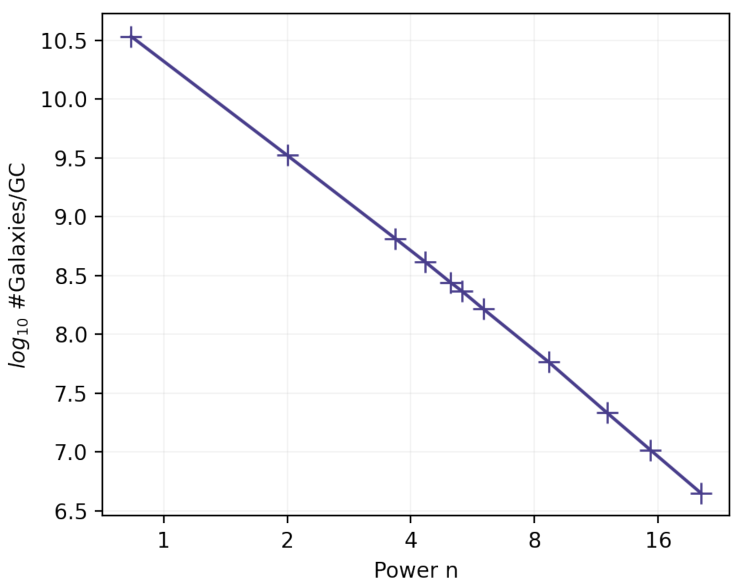

Figure 12. Average number of galaxies within volume controlled by each GC, after all volume is controlled by GCs. We apparently live on a one-in-ten-million-plus-galaxies "rare Earth" (15).

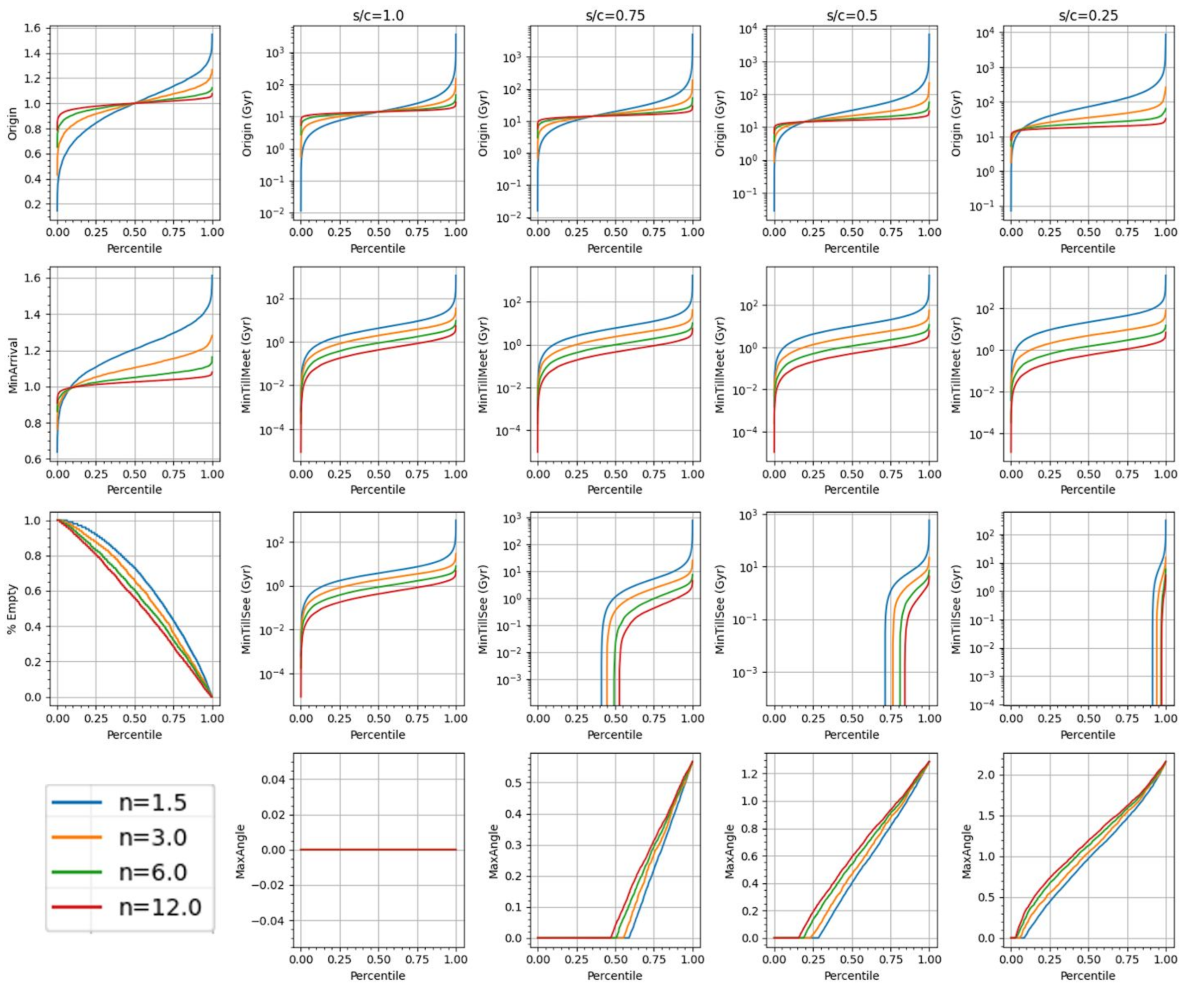

Figure 13. C.d.f.s of many GC statistics for four powers n and four speed ratios s/c. The mappings used between model and clock times all update on the fact that we don't now see aliens, but the c.d.f.s show all GCs. Each c.d.f. here is based on a single simulation run.

Note that the higher the power, the more closely spaced are GC origin times, the fewer galaxies each GC encompasses, and the sooner until we meet or see them.

13 Conclusion

A literature has modeled the evolution of life on Earth as a sequence of "hard steps", and compared specific predictions of this model to Earth's historical record. This model seems to fit, and supports inferences about the number of hard steps so far experienced on Earth. As far as we can tell, this model seems widely accepted, without published criticisms.

We argue that this standard hard-steps model has not been taken sufficiently seriously. For example, the literature on the "galactic habitable zone", which often estimates the timing of the appearance of advanced life in a galaxy, has never included the key hard-steps effect that the chance of success by a deadline goes as a power law. In Section 4 we have shown a simple model which includes this effect, wherein humanity today seems to be early, unless one assumes both a rather low power *and* a very restrictive limit on habitable planet lifetimes.

Related literatures have also apparently not considered applying this hard-steps-based power law to larger volumes like galaxies, instead of to just planets. Some authors have suggested that big sterilizing explosions may allow a scenario wherein galaxies long stayed empty, and have only recently been filling up with civilizations as such explosions have waned. But these authors do not seem to have realized that, with a sufficiently high power, a volume-based hard steps power law produces a similar scenario (if on a larger scale) without invoking sterilizing explosions. Nor have they noticed that a scenario wherein advanced civilizations grab most of the available volumes soon seems required to explain our early arrival.

To formalize this argument, we have presented in this paper a simple model of what we call "grabby" civilizations (GC), who are born according to a volume-based power law and who once born simply expand at a constant speed relative to local materials. This speed and the two parameters of this power law are the only three parameters of our model, each of which can be estimated to within roughly a factor of four.

The hard-steps literature helps estimate the power, and our current date helps estimate the power law timescale. Furthermore, the fact that we do not now see large alien-controlled volumes in our sky, even though they should control much of the universe volume now, gives us our last estimate: that aliens expand at over half of lightspeed. Given estimates of all three parameters, we have in this paper shown many model predictions regarding alien timing, spacing, appearance, and the durations until we see or meet them.

Being especially simple, our model is unlikely to be an exact representation of reality. So future research might explore more realistic variations. For example, one might better account for the recent exponential expansion of the universe. Instead of being uniform across space, the GCs birth rate might be higher within galaxies, more within larger galaxies, and follow their typical spatial correlations. The expansion might take a duration

to bring its full effect to any one location, and the expansion speed might vary and depend on local geographies of resources and obstacles. Finally, GC subvolumes might sometimes stop expanding or die, either spontaneously or in response to local disturbances.

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14 Appendices

Figure 14 varies box length L, holding constant $s = 1$, to see if border effects cause problems due to the wrap-around metric. $L = 1$ seems sufficiently large.

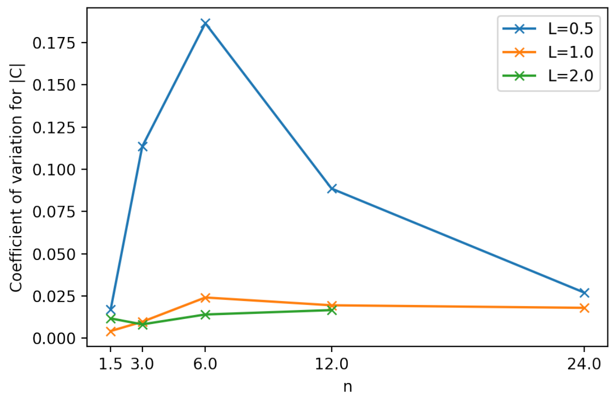

Figure 14. Testing if L=1 is sufficiently large, when s=1.

	Scenario: $s/c = 1/2,\ n = 6$			*Scenario:* $s/c = 3/4,\ n = 12$		
Percentile	*1%*	*25%*	*75%*	*1%*	*25%*	*75%*
Origin	0.810	0.955	1.036	0.893	0.977	1.019
MinArrival	0.932	1.022	1.076	0.962	1.011	1.038
MinSee	0.855	0.937	0.985	0.936	0.984	1.014
Origin (Gyr)	8.99	15.25	21.24	10.20	13.46	16.02
MinTillMeet (Gyr)	0.019	0.488	2.226	0.006	0.188	0.882
MinTillSee (Gyr)	0	0	0	0	0	0.425
MaxAngle	0	0.132	0.908	0	0	0.313
% Empty	0.010	0.320	0.830	0.010	0.290	0.810

Table 1. Specific numbers for two scenarios, $(n, s/c) = (6, 1/2), (12, 3/4)$.

For those frustrated by difficulties in reading numbers off our many graphs, Table 1 gives specific numbers for two scenarios.

As discussed in Section 8, most of our simulations have assumed a power law cosmological scale factor of $a(t) = t^m$, with $m = 2/3$. Figure 15 shows how some of our results change when $m = 0.9$ instead. It seems that the main effect is to, in effect, increase the power n. Figure 16 shows how both of these power law approximations compare to the actual scale factor $a(t)$.

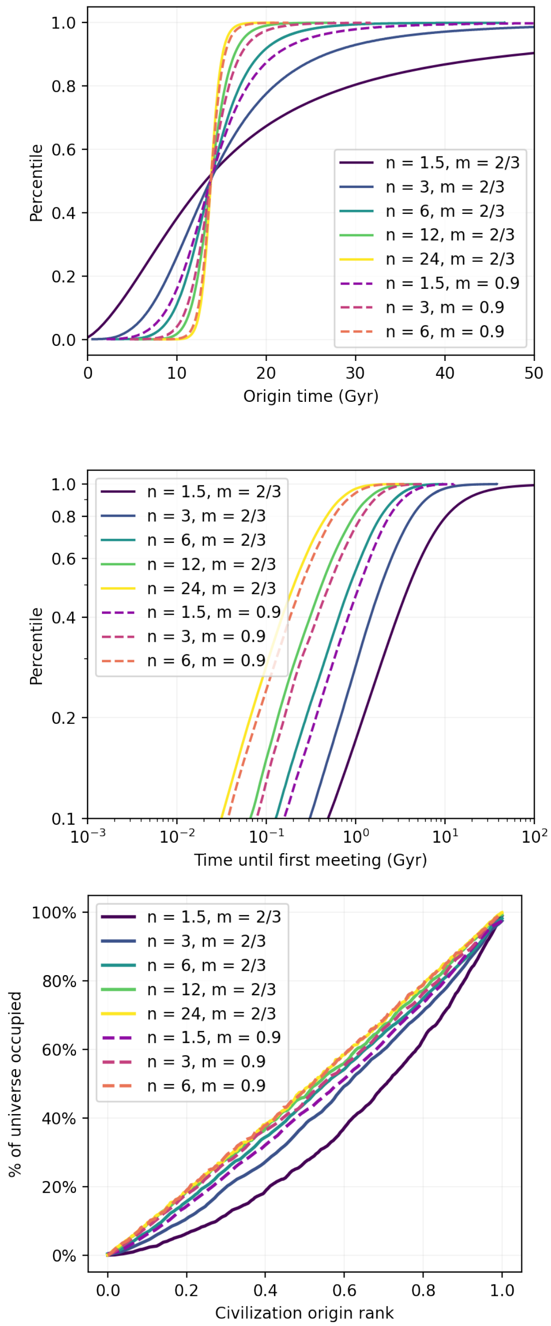

Figure 15. Comparing results for cosmological scale factor powers of $m = 2/3$ and $m = 0.90$.

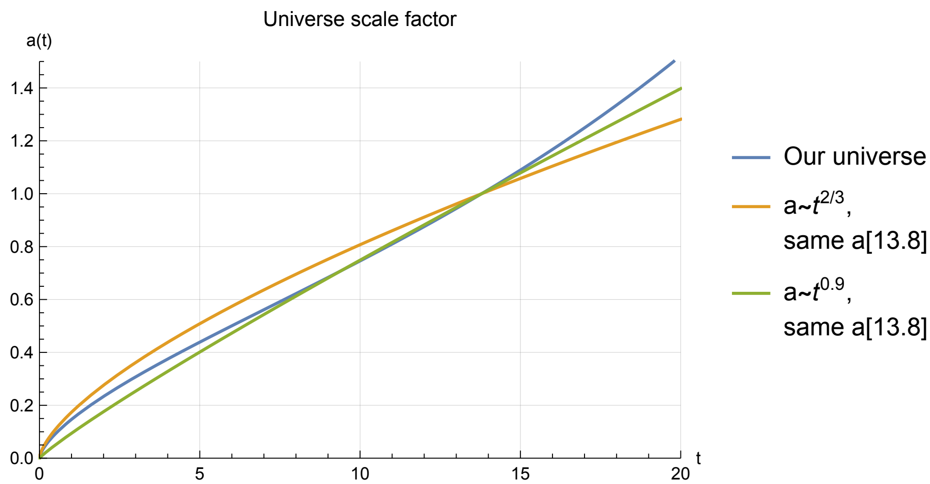

Figure 16. Cosmological scale factor over time, in reality and as assumed in this paper.

Figure 17 shows robustness of our earliness estimates to varying the GHZ peak, by comparing the three values of peak χ in $4, 8, 12$ Gyr, all given MFP $\kappa = 0$.

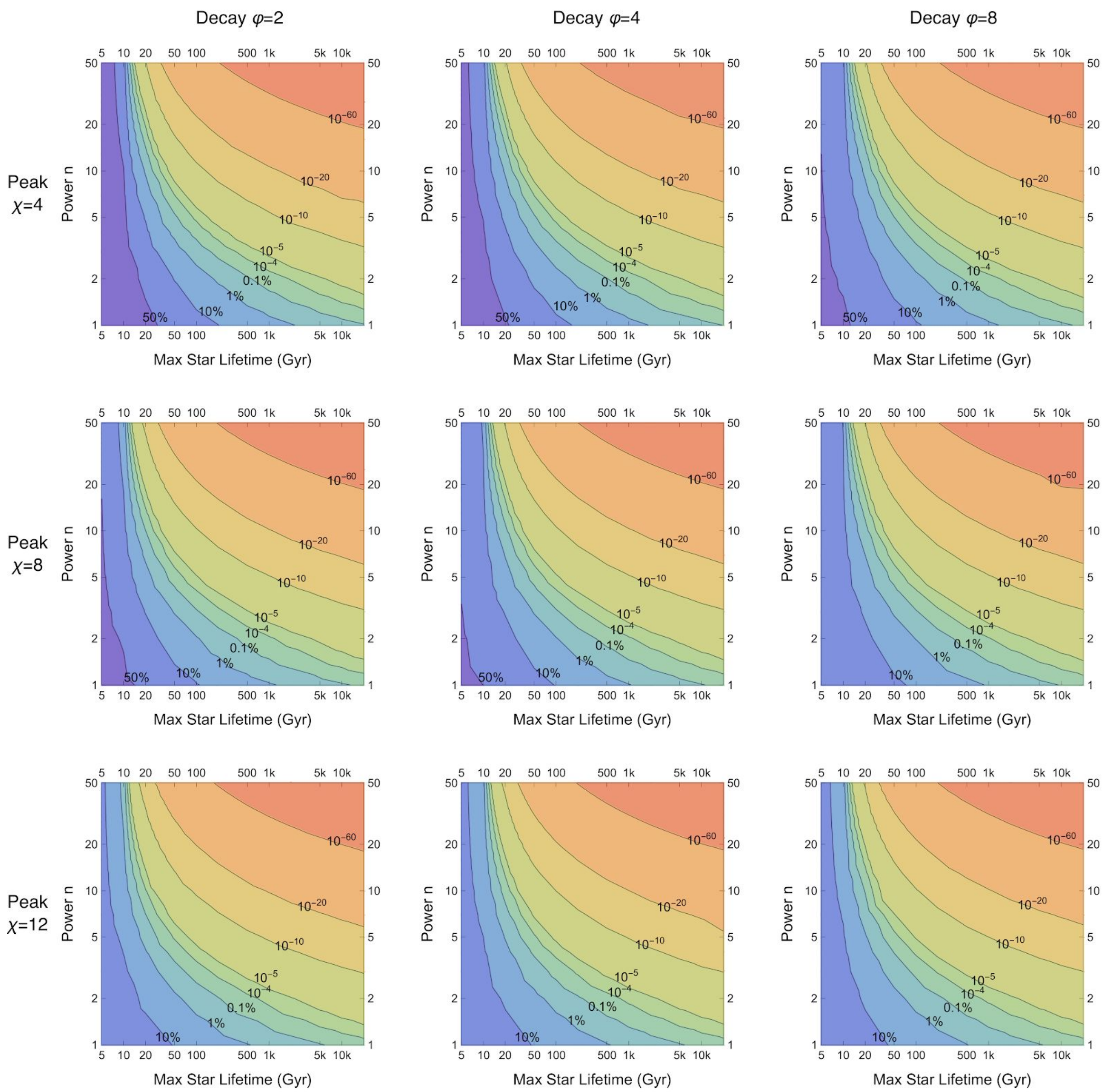

Figure 17. Percentile rank of today's 13.8Gyr date within the distribution of advanced life arrival dates, as given by equation (1), assuming MFP $\kappa = 0$. Nine diagrams show different combinations of GHZ peak χ and decay φ, while each diagram varies power n and max habitable planet lifetime $\bar{L}$.